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Evidence from Intrinsic Shapes for Two Families of Elliptical Galaxies

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ABSTRACT

Bright elliptical galaxies have a markedly different distribution of Hubble types than faint ellipticals; the division occurs near $M_B = -20$ and bright ellipticals are rounder on average. The Hubble types of galaxies in both groups are narrowly clustered, around E1.5 in the case of the bright galaxies and around E3 for the fainter ones. The Hubble-type distribution of the faint ellipticals is consistent with oblate symmetry, but the oblate hypothesis fails for the bright ellipticals. However a distribution of triaxial intrinsic shapes can successfully reproduce the apparent shape data for either group. The distribution of intrinsic, short-to-long axis ratios is peaked around 0.75 for bright galaxies and 0.65 for faint galaxies. Our results provide further evidence that elliptical galaxies should be divided into two, morphologically distinct families.

1. Introduction

In a previous paper (Tremblay & Merritt 1995, hereafter Paper I) we presented a nonparametric technique for estimating the frequency function of elliptical galaxy intrinsic shapes. We showed that the Djorgovski (1985) - Ryden (1992) axis ratio data for 171 elliptical galaxies was strongly inconsistent with the axisymmetric hypothesis but consistent with a number of triaxial shape distributions. The distribution of Hubble types was found to be broad or bimodal, with weak maxima near E1 and E3. Similar conclusions were reached by Fasano & Vio (1991) and by Ryden (1992, 1996), using the same and other data sets.

It has been clear for some time that faint elliptical galaxies are kinematically and morphologically distinct from brighter ellipticals, and this difference might be expected to manifest itself in the respective distributions of axis ratios. Elliptical galaxies brighter than $M_B \approx -20$ are generally slowly rotating, while fainter ellipticals exhibit roughly as much

rotation as would be expected if their figures were centrifugally flattened (Davies *et al.* 1983). Faint ellipticals also tend to exhibit disklike distortions and peaked, central density profiles, while bright ellipticals are more often "boxy" with shallow central profiles (Nieto *et al.* 1991; Kormendy et al. 1995). It is natural to assume that fainter ellipticals are oblate spheroids flattened by rotation, while bright ellipticals might be triaxial, since in the absence of dynamically significant rotation there is no strong *a priori* case to be made for oblate symmetry (Binney 1978).

Here we extend the analysis of Paper I by investigating the dependence of the elliptical galaxy axis-ratio distribution on intrinsic luminosity. We combine the Djorgovski - Ryden data set with Lauer & Postman's (1994) sample of brightest cluster galaxies, whose intrinsic shape distribution was studied by Ryden, Lauer & Postman (1993). We find that the sample is effectively divided into two populations, with the division occurring near $M_B = -20$. Brighter ellipticals have Hubble types that are narrowly clustered around E1-E2, while fainter ellipticals have Hubble types near E3. Combining bright and faint galaxies into one sample produces the broad or double-peaked distribution seen in Paper I and in other studies. Furthermore, we find that while the distribution of Hubble types for the fainter ellipticals is consistent with oblate symmetry, the oblate hypothesis fails for the brighter ellipticals. However a distribution of triaxial intrinsic shapes can be found that reproduces the apparent shape data for either subset of galaxies. Thus the frequency function of apparent axis ratios is consistent with – though does not strictly imply – a model in which fainter ellipticals are oblate and moderately flattened, while brighter ellipticals are rounder and triaxial.

2. Data

Our first set of galaxies is the sample introduced by Ryden (1992), itself extracted from a program of CCD photometry of bright ellipticals carried out by Djorgovski (1985). As in Paper I, we continue to use the luminosity-weighted mean axis ratios defined by Ryden (1992).

We obtained apparent magnitudes of the galaxies in the Djorgovski-Ryden sample from de Vaucouleurs *et al.* (1991, hereafter RC3). We needed reliable, redshift-independent distances to each galaxy in order to determine their absolute magnitudes – defined throughout this study as total (asymptotic) blue magnitudes M_B. The majority of the galaxies in this sample have a distance derived from the Dn-σ relation (Dressler *et al.* 1987). Our Dn-σ distances came from the Mark II electronic release catalogue of Burstein (1995) and from Faber *et al.* (1989). A handful of the galaxies in the sample had their

distances measured using the surface brightness fluctuation (SBF) method (Tonry and Schneider 1988). The tabulated Dn-σ distances are given in terms of corrected redshift velocities; we converted these redshifts to Mpc using a Hubble constant such that the resulting distance to the Virgo cluster is equal to 16 Mpc, equivalent to the SBF distance (Tonry, Ajhar & Lupino 1990), and in agreement with recent Cepheid data (Freedman *et al.* 1994; Pierce *et al.* 1994). A total of 107 galaxies from the Djorgovski-Ryden sample had redshift-independent distance estimates from one of these sources.

To this sample we added the 119 galaxies in the Lauer & Postman (1994) sample of brightest cluster galaxies. Luminosity-weighted axis ratios for these galaxies are given in Ryden, Lauer & Postman (1993) and absolute magnitudes in Lauer & Postman (1994). Six galaxies were found to be in both samples, giving a total of 220 galaxies in the combined set.

We carried out the analysis described below with both the combined sample, and with the Djorgovski-Ryden data alone. Aside from the smaller degree of noise in the larger sample, we found no significant differences; hence we present results from only the combined sample below.

3. Analysis

We define $f(q, M_B)$ to be the joint distribution of elliptical galaxy apparent axis ratios q, $0 < q \leq 1$, and absolute magnitudes M_B. Our goal is to construct an estimate of f, which we call $\hat{f}$, from the data, then to operate on $\hat{f}$ to obtain estimates of the intrinsic shape distribution at any M_B. The numerical inversion techniques for the last step are described in Paper I.

The estimation of multivariate density functions is the subject of much current research in nonparametric statistics. We used an "adaptive product kernel" estimator (Scott 1992, p. 149) on the set of pairs (q, M_B) to produce the estimate $\hat{f}(q, M_B)$. This estimator has the form

$$\hat{f}(q, M_B) = \frac{1}{n h_q h_M} \sum_{i=1}^{n} \left[l_i^{-2} K\left(\frac{q - q_i}{h_q l_i}\right) \times K\left(\frac{M_B - M_{Bi}}{h_M l_i}\right)\right] \tag{1}$$

where q_i and M_{Bi} are the apparent axis ratio and absolute magnitude of the i^{th} galaxy. The function K is called a kernel, and converts the discrete data into a smooth continuous function. We used the quartic kernel:

$$K(x) = \begin{cases} \frac{15}{16}\left(1 - x^2\right)^2, & -1 \leq x \leq 1; \\ 0, & \text{otherwise.} \end{cases}$$

The quantities h_q and h_M are the window widths of the respective variables, which must be chosen correctly if the estimate $\hat{f}$ is to lie close to the "true" function f. The quantity l_i is a dimensionless variable which adapts the window widths as a function of local density. It is defined as

$$l_i = \left[\frac{\tilde{f}(q_i, M_{Bi})}{g}\right]^{-1/2},$$

where $\tilde{f}(q_i, M_{Bi})$ is a "pilot estimate" of the density obtained using a fixed window width (h_q, h_m), and g is the geometric average of the $\tilde{f}(q_i, M_{Bi})$. As is usually done, we reflected the data about the $q = 1$ axis before constructing the estimates.

In Paper I we applied the "unbiased cross-validation" method (UCV) to determine the optimal smoothing parameters in our one-dimensional study. This method is readily adaptable to higher dimensions (e.g. Silverman 1986, p. 87). The dependence of the UCV on the two smoothing parameters h_q and h_M for our sample is shown in Figure 1. The smoothing parameters giving the minimum value of the UCV are $(h_q, h_M) = (0.11, 0.8)$. The resulting, optimal estimate of the density $\hat{f}(q, M)$ is shown in Figure 2. We have normalized $\hat{f}$ such that its integral along q is unity at every fixed M_B – the distribution of absolute magnitudes is of no interest to us here.

Figure 2 shows two clear peaks: one near $q = 0.85$ for the bright galaxies ($M_B \leq -20$), and one near $q = 0.7$ for the fainter galaxies. Cuts of $\hat{f}(q, M_B)$ at three values of M_B are shown in Figure 3. The narrowness in q of the bright-galaxy distribution is especially striking; the profile is well approximated as a Gaussian with a dispersion of only 0.08 about the median value $q \approx 0.85$. This dispersion is roughly equal to the adopted smoothing bandwidth in q which implies that the real distribution may be even *more* strongly peaked in q than Figure 3 suggests.

The result of Paper I – a broad or bimodal distribution $f(q)$ – can now be more completely understood: $f(q)$ consists of the superposition of two unimodal distributions, which have peaks at different values of q for the bright and faint subsamples.

In Paper I we showed that the rapid falloff in $f(q)$ near $q = 1$ was inconsistent with the axisymmetric hypothesis for galaxy intrinsic shapes. Such a falloff is seen here (Figure 3) in the bright-galaxy subsample but not in the faint galaxies. Estimates of the distribution of intrinsic axis ratios $\hat{N}(\beta)$ under the oblate and prolate hypotheses are shown in Figure 3 for three values of M_B; the dashed lines are 95% bootstrap confidence bands. (As discussed in Paper I, the estimates $\hat{N}$ are deconvolutions of $\hat{f}$ and should be constructed from estimates of f that were obtained using larger values of the smoothing parameters than the "optimal" values derived above. We chose $h_q = 0.15$ when constructing $\hat{f}$ for use in computation of $\hat{N}$.) The oblate and prolate hypotheses are both inconsistent at the 95% level with the

Hubble type distribution of the bright galaxies, but both are consistent with the faint galaxies.

As in Paper I, one might hope to successfully reproduce the Hubble-type distribution for the brighter ellipticals using a triaxial distribution of intrinsic shapes. Figure 4 shows the result. We have assumed that all galaxies are triaxial to the "same" degree, i.e. characterized by a fixed value of $Z = \frac{1-\beta_1}{1-\beta_2}$, with β_1 and β_2 the two axis ratios, $1 \geq \beta_1 \geq \beta_2$. Under such an assumption, one can indeed invert $\hat{f}(q)$ for the bright galaxies (as well as the fainter ones) without forcing $\hat{N}(\beta_2)$ to go negative near axis ratios of unity.

4. Discussion

Our primary result is that the distribution of Hubble types is significantly different for bright and faint elliptical galaxies, with the division occuring near $M_B = -20$. Both families of galaxy exhibit unimodal distributions of apparent shapes, with the peak lying near E1.5 for bright ellipticals and near E3 for faint ellipticals. The broader distributions seen in Paper I and in earlier studies may be interpreted as superpositions of these two, narrower frequency functions.

The distribution of Hubble types of the fainter ellipticals is consistent with the oblate, prolate and triaxial hypotheses; the intrinsic shape distribution inferred under any of these hypotheses has a peak in c/a between 0.6 and 0.7. The Hubble-type distribution of the bright ellipticals is inconsistent with the axisymmetric hypothesis but is reproducable if one assumes triaxiality; the intrinsic shape distribution is sharply peaked at a short-to-long axis ratio of about 0.75.

Our results are consistent with earlier intrinsic-shape studies that examined luminosity-selected groups of elliptical galaxies. Ryden, Lauer and Postman's (1993) estimate of $f(q)$ for the subset of 119 brightest cluster galaxies included here looks quite similar to our estimate $\hat{f}(q, M_B)$ at $M_B = -20.5$, with a single peak near $q = 0.83$ and a rapid falloff for q near one. Dwarf ellipticals (dE's), on the other hand, appear to be flatter on average than normal ellipticals (Ryden & Terndrup 1994), similar to our result for low-luminosity E's. However dwarf ellipticals differ in many fundamental ways from brighter, "normal" ellipticals and it is not clear that the two groups should be compared. Fasano (1991) analyzed small samples of boxy and disky ellipticals and found weak evidence for a difference in the apparent ellipticity distributions; the difference was qualitatively similar to what is seen here between bright and faint subsamples.

Our findings are consistent with a model in which fainter ellipticals are moderately

flattened, oblate spheroids while bright ellipticals are more nearly round and triaxial. However such a model is not compelled by our analysis since the Hubble-type distribution for the faint ellipticals is equally consistent with the triaxial hypothesis. Nevertheless, the division of the *apparent* shape distribution into two groups at $M_B \approx -20$ is robust and implies a corresponding change in the distribution of intrinsic shapes at roughly this luminosity.

Our results contribute to the growing body of evidence that elliptical galaxies can be divided into two families that are morphologically and kinematically distinct (Bender 1988; Nieto, Bender & Surma 1991; Kormendy et al. 1995). A number of plausible formation scenarios for these two families are consistent with our results. A greater role for dissipation in the formation of faint ellipticals would cause these galaxies to be both more highly flattened and more strongly rotating – and possibly more oblate – than bright ellipticals. Bright ellipticals might form through the mergers of fainter galaxies, a process that would likely make them rounder, more slowly-rotating and possibly more triaxial than low-luminosity ellipticals.

Questions of formation aside, one can make inferences about intrinsic shapes based purely on the requirements of dynamical equilibrium. Elliptical galaxies fainter than $M_B \approx -20$ have steep central density cusps, $\rho \propto r^{-\gamma}$, $1 \lesssim \gamma \lesssim 2$; bright ellipticals have shallower cusps, $0 \lesssim \gamma \lesssim 1$ (Merritt & Fridman 1995; Gebhardt et al. 1996). Cusps steeper than $\gamma \approx 1$ will induce most of the boxlike orbits in a triaxial galaxy to behave chaotically over astronomical timescales (Merritt & Valluri 1996). One result is that triaxiality is difficult to maintain in a galaxy with a steep cusp (Merritt & Fridman 1996). The change in the shape distribution seen here — also near $M_B = -20$ — might reflect in part the influence of the central cusps on the global shapes. However this mechanism would not naturally explain why the more triaxial galaxies are less flattened.

The remarkably narrow distributions of axis ratios which we find at both high and low luminosities were quite unexpected. It is important to understand what this result might imply about the formation of elliptical galaxies.

B. Ryden kindly supplied the luminosity-weighted axis ratios used here and in Paper I, and prompted us to combine the Lauer-Postman sample with her own data. D. Burstein sent us his Mark II library of estimated galaxy distances and advised us in how to use it. This work was supported by NSF grant AST 90-16515 and NASA grant NAG 5-2803 to DM.

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Fig. 1.—

Contours of UCV (see text) for various smoothing parameters. Contours are separated by 0.005; the cross indicates the position of the minimum.

Fig. 2.—

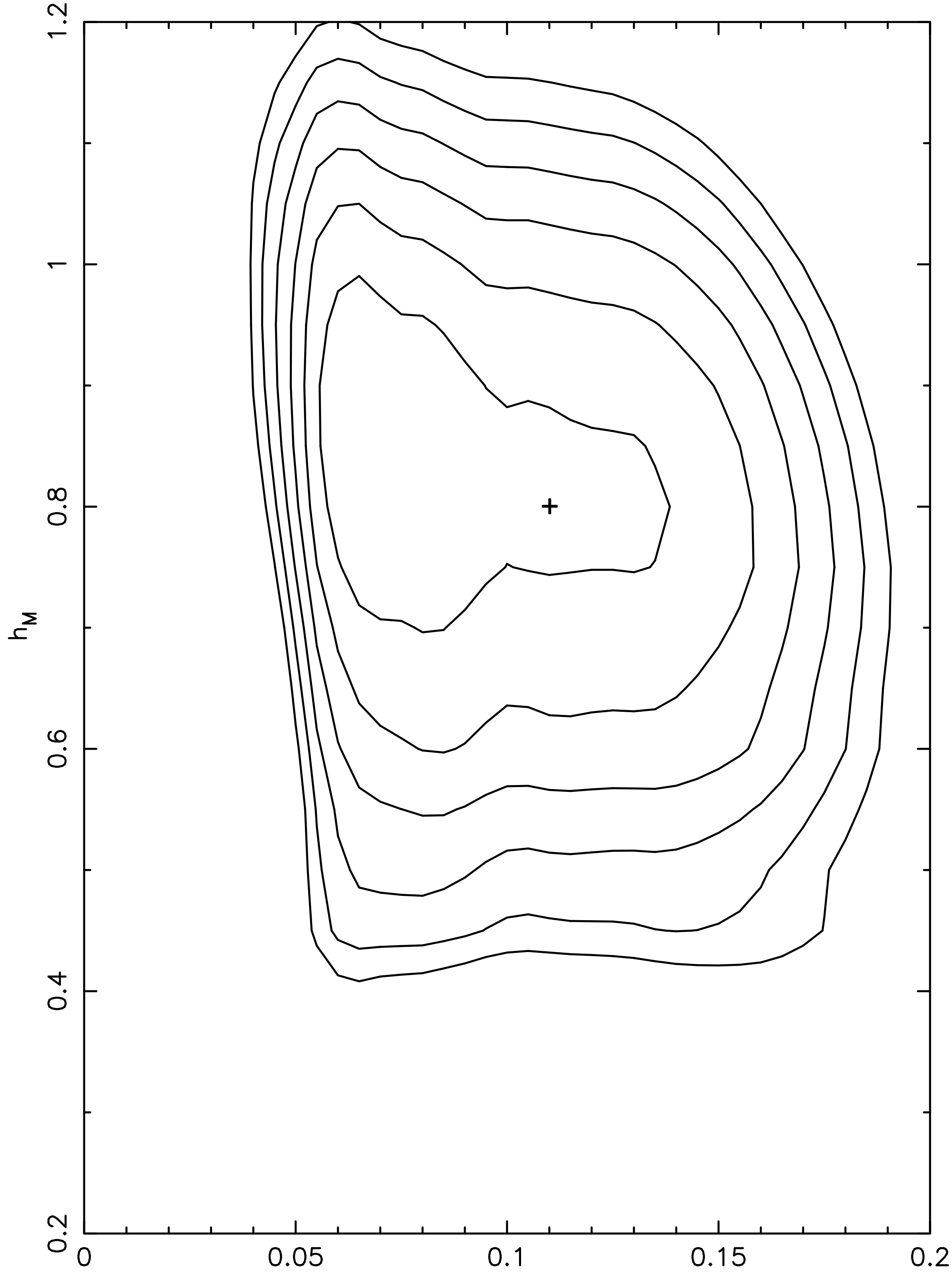
Estimate of $f(q, M_B)$ for the 220 galaxies in our sample, obtained via a product-kernel technique with different window widths in the q and M_B directions. The function f has been normalized at every M_B to give unit area when integrated along q. Circles are galaxies in the Djorgovski-Ryden sample; dots are from the Lauer-Postman sample. The six galaxies in both samples are indicated by circles. Contours are separated by 0.5 in f.

Fig. 3.—

The dependence of the frequency function $\hat{f}(q, M_B)$ on q at three values of M_B, and its oblate and prolate deconvolutions. a) $M_B = -18.5$; b)$M_B = -19.5$; c) $M_B = -20.5$. Dashed lines are 95% confidence bands on the estimates.

Fig. 4.—

The dependence of the frequency function $\hat{f}(q, M_B)$ on q at three values of M_B, and its deconvolution under the assumption that all galaxies are triaxial to the same degree, $Z = (1 - b/a)/(1 - c/a) =$ constant. a) $M_B = -18.5$; b)$M_B = -19.5$; c) $M_B = -20.5$. Dashed lines are 95% confidence bands on the estimates.



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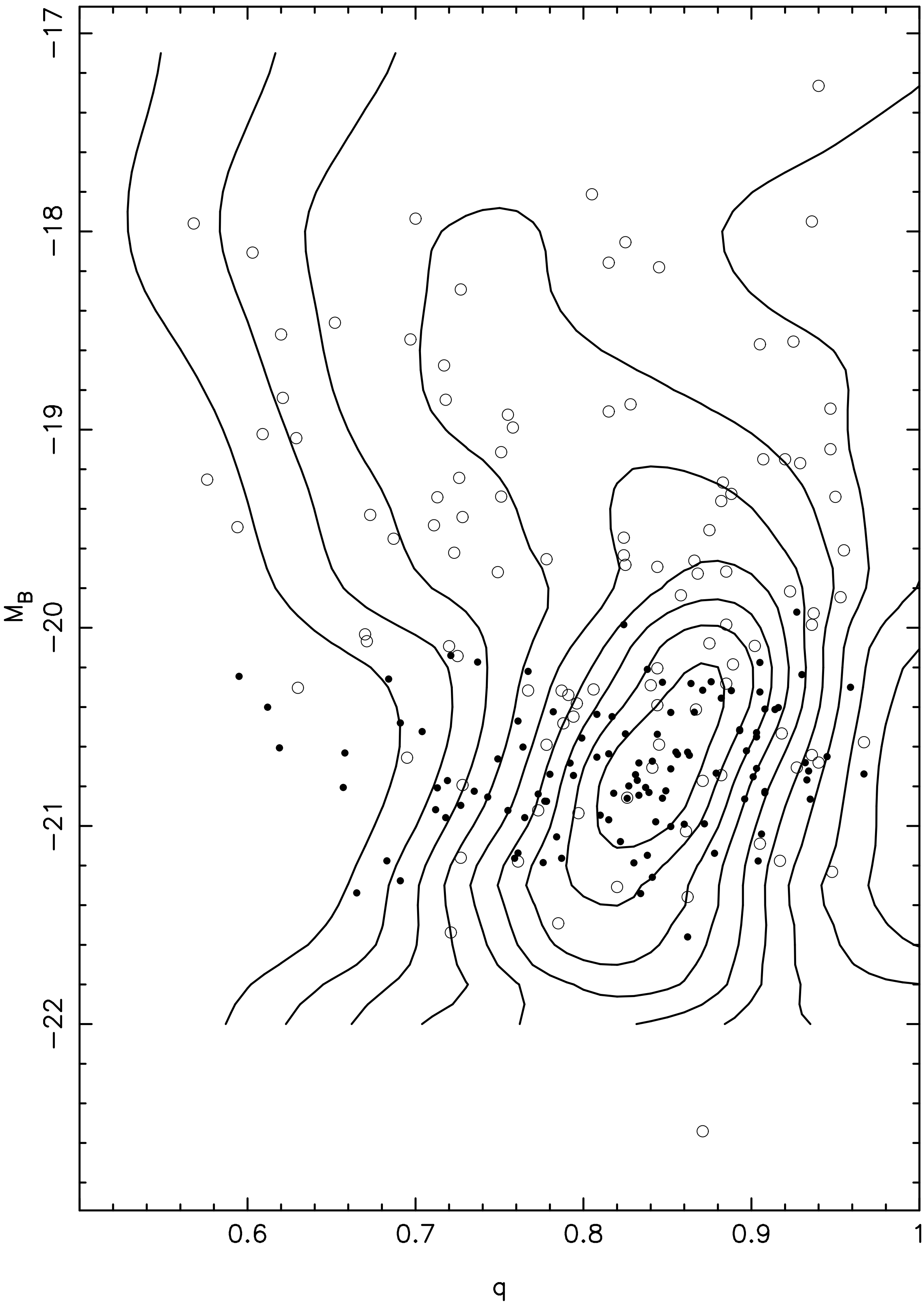

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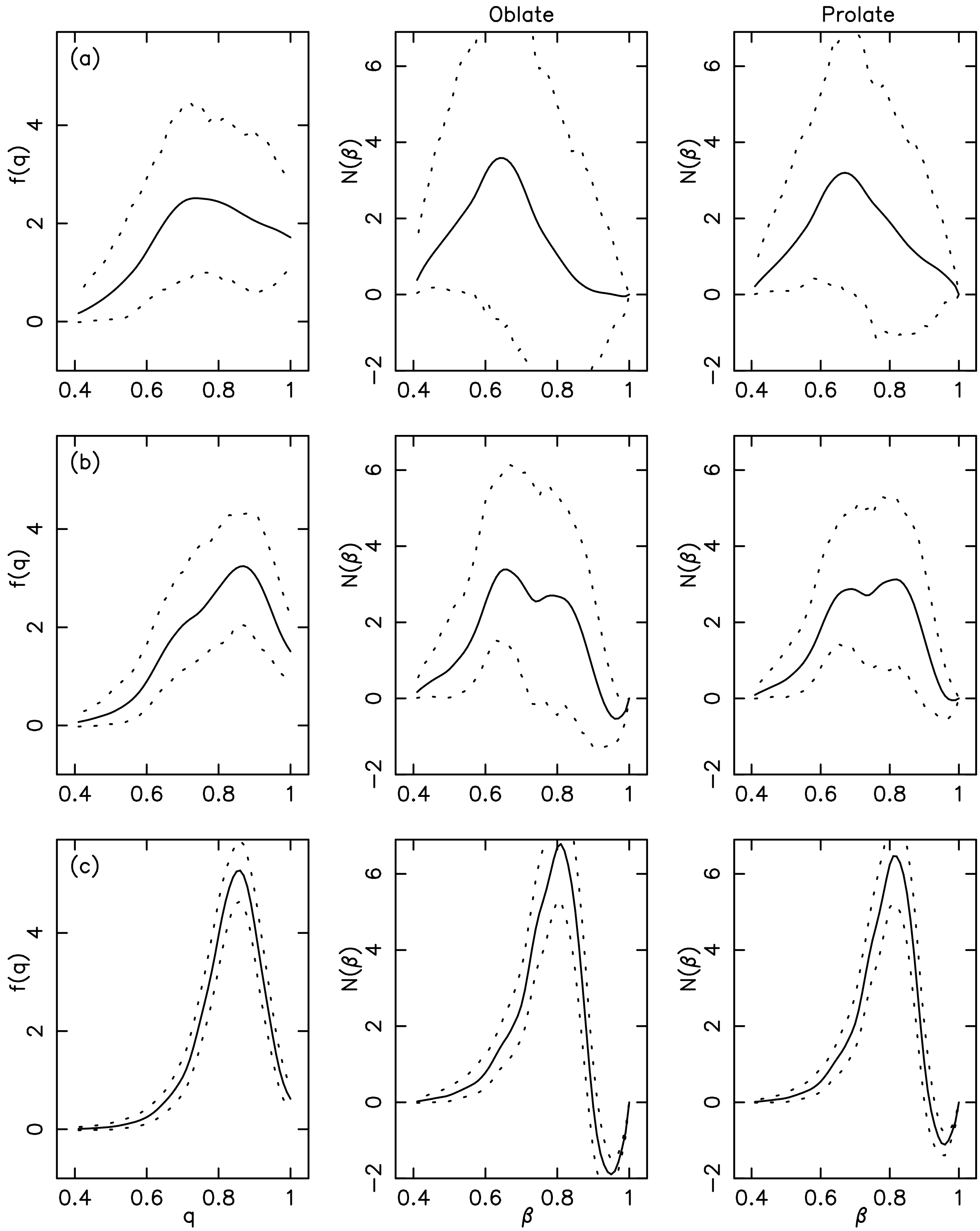
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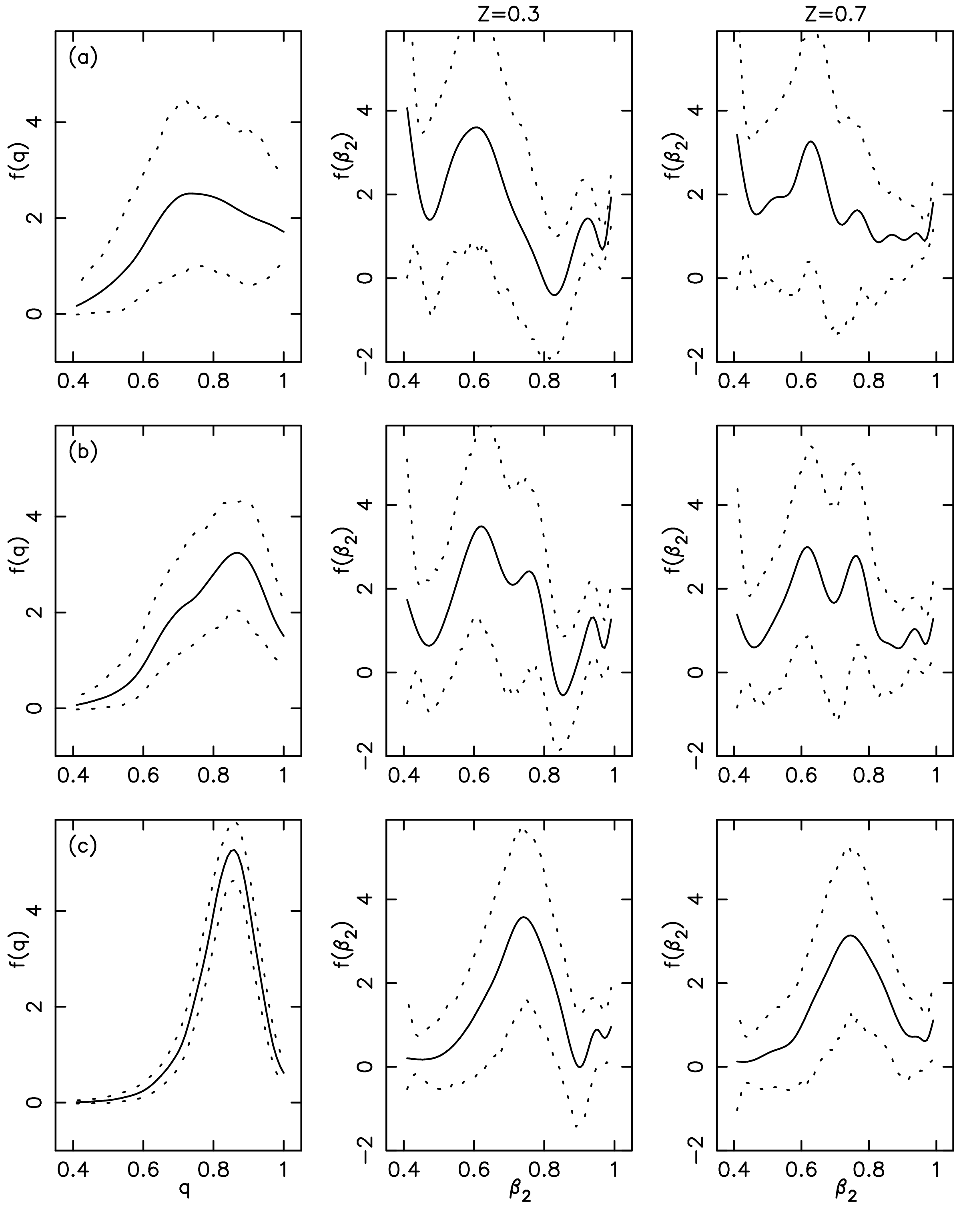
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